2012

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Published in *Global and Planetary Change* 96-97(2012) doi:10.1016/j.gloplacha.2012.01.013

Submitted June 3, 2010; accepted January 24, 2012; published online June 26, 2012

A diatom record of late Pliocene cooling from the Ross Sea continental shelf, AND-1B, Antarctica

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Abstract
A late Pliocene – early Pleistocene, 2.9–2.0Ma, diatom record from the Antarctic Geological Drilling Program (ANDRILL) MIS drillcore AND-1B is presented. This core, recovered from beneath the Ross Ice Shelf south of Ross Island, comprises multiple diatomaceous-sediment units deposited during interglacial periods with open water over the core site. These represent interglacial phases of orbitally paced climate cycles and are punctuated by glacial advances. Extant diatom assemblages have limited presence in the late Pliocene record, which makes environmental interpretation less straight forward. We employ modern ecological data in combination with late Pliocene to present variation in diatom assemblages across the Southern Ocean oceanic fronts based on DSDP/ ODP diatom biostratigraphic data to evaluate paleoenvironmental change for the 2.9–2.0Ma interval of the AND-1B core. The diatom assemblages from AND-1B record a progressive environmental change through the late Pliocene–early Pleistocene. A relatively warm period with potential SST of up to 4°C at ca. 2.9Ma was succeeded by a reduction of warm water species and an increase of taxa associated with more southerly water masses until 2.58Ma (at isotope stage G1). Younger, early Pleistocene, diatomaceous units are dominated by extinct *Rouxia, Thalassiosira* species and newly described *Fragilariopsis* species indicative of cold open water and drift ice. The last recorded cooling step occurs at the top of the interval studied (ca 2.0) Ma indicated by the trace abundance of *Fragilariopsis* and *Actinocyclus* species present in modern sea ice assemblages but absent in the late Pliocene–early Pleistocene AND-1B record, even though many of its species had their first occurrences during the Pliocene. The extant sea ice assemblage occurs with an abundance of 2–29% (average 10%) in the late Pliocene–early Pleistocene AND-1B record implying that the modern sea ice and ice shelf polar conditions were not established within the studied interval. The most frequently applied sea ice indicator, *Fragilariopsis curta*, is consistently present in low to moderate abundance (1–22%) together with *Chaetoceros* resting spores (2–30%) through the 2.9–2.0Ma interval. The diatom assemblage shifts indicate a dynamic environment with an overall trend towards colder conditions after ca. 2.6Ma but does not reach the Holocene configuration.

Keywords: ANDRILL, late Pliocene, Antarctica, diatom, climate change, Ross Sea

1. Introduction

The early to mid-Pliocene is widely accepted as a period of global warmth compared to the present; as such it is receiving a lot of interest as a case study for future anthropogenic warming (Crowley, 1996; Dowsett et al., 2005; Haywood et al., 2009). Most extensively studied is the Pliocene Research Interpretation and Synoptic Mapping (PRISM) mid-Pliocene interval 3.3–3.0Ma (Crowley, 1996; Dowsett et al., 2005). The PRISM2 model and δ18O records show increased sea surface temperature (SST) especially at high latitudes and mean annual temperatures may have been as much as 3–4°C warmer and with global sea level 25–35m above present (Crowley, 1996; Ravelo et al., 2004; Dowsett et al., 2005). The extent of Pliocene warming in the Antarctic continental shelf area has been poorly documented due to the lack of well-preserved marine sediment from cores containing this interval. The coastal and terrestrial Cenozoic Investigation in the Western Ross Sea (CIROS) and the Dry Valley Drilling Project (DVDP) cores from McMurdo Sound, Ross Sea, comprise truncated diatom-bearing early and mid-Pliocene sequences (Winter and Harwood, 1997; Winter et al., 2010a) and the Deep Sea Drilling Project (DSDP) Leg 28 Site 271 from Eastern Basin, Ross Sea comprise a sporadic late Pliocene record with only 7% recovery (Hayes et al., 1975). Some evidence for late Pliocene warm periods was encountered in Prydz Bay by Ocean Drilling Program (ODP) Legs 113 and 188 (Mahood and Barron, 1996; Whitehead et al., 2005), from an uplifted marine sequence in the Pagodroma Group, Prince Charles Mountains, East Antarctica (Whitehead et al., 2004) and Cockburn Island, Antarctic Peninsula (Jonkers and Kelley, 1998). These records are too few and sporadic to provide a comprehensive view of late Pliocene climate on the Antarctic continental shelf. The AND-1B core from the McMurdo Ice Shelf south of Ross Island (Fig. 1) comprises much

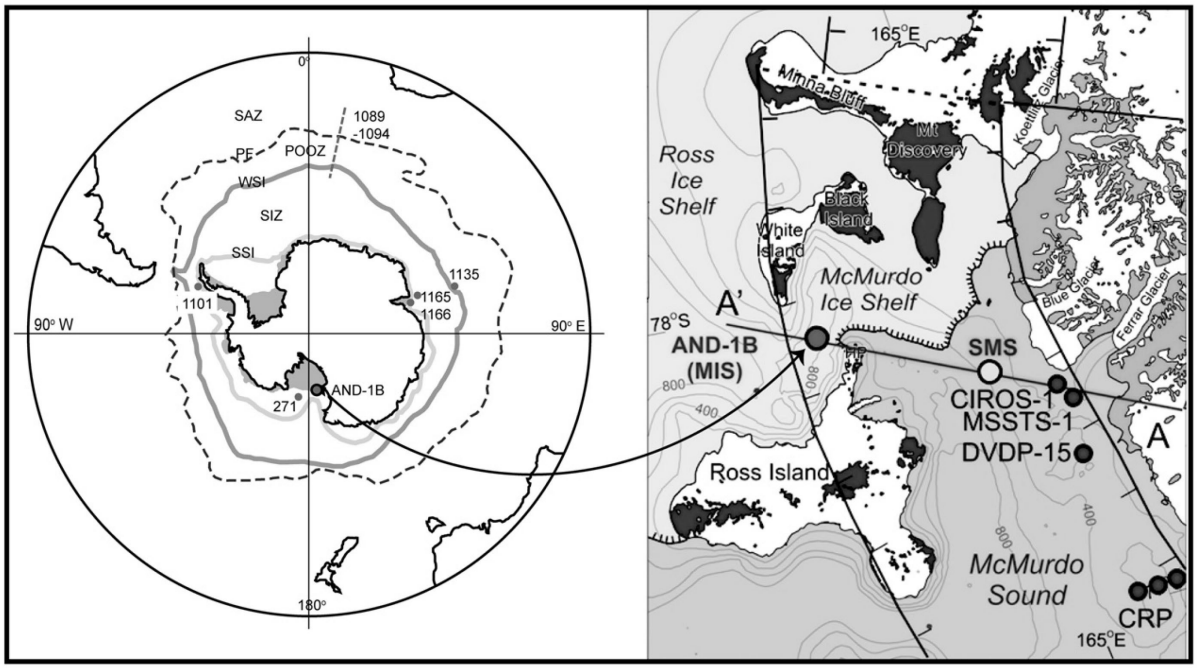

Figure 1. Map of Antarctica with sea-ice limits and oceanic fronts: SSI=average Summer Sea-Ice, SIZ=Seasonal Sea-Ice Zone, WSI=average Winter Sea-Ice, POOZ=Permanent Open Ocean Zone (similar to PFZ=polar front zone), PF=Polar Front (adapted from Armand et al., 2005). Also marked are the sites used for Fig. 3, our comparative paleoenvironmental interpretation. Inset shows Ross Island and the AND-1B core site together with some of the earlier coring sites in this region.

of the late Pliocene–early Pleistocene[1] record previously not recovered from the Ross Sea, it also fills a significant gap in Antarctic climate history and serves as a tie point for previously recovered cores. This core preserves a unique record of cyclic periods of open water deposition of diatomite and diatomaceous mud in the Ross Sea from ca. 4.9–2.0Ma (Naish et al., 2007, 2009; Scherer et al., 2007). The sedimentologic record shows a progressive cooling through the Pliocene and Pleistocene characterized by three stages; 1) open water, no ice shelf or sea ice, 2) advance and retreat of a dynamic subpolar ice sheet (3.4–2.6Ma) (e.g. late Pliocene this paper), and 3) advance and retreat of a subpolar ice sheet with less meltwater and presence of ice shelves (2.6–1Ma) (Naish et al., 2009).

Ecological exclusion and poor preservation of other microfossil groups in Pliocene and Pleistocene Antarctic sediment renders diatoms the main biogenic tracer for past ocean surface water conditions and SST. During initial investigation it became evident that the diatom flora underwent dramatic change over time reflecting a highly dynamic Pliocene environment (Scherer et al., 2007). Here we evaluate the diatom record from 2.9 to 2.0Ma, a key time period for understanding the transition from the warmer-than-present mid-Pliocene to the fully polar conditions of the late Pleistocene persisting to the present. The importance of this record is that it holds information of the Antarctic environment prior to and following development of the first Northern Hemisphere ice sheets at ca. 2.7Ma. (Maslin et al., 1998). From terrestrial evidence in the Dry Valleys it is suggested that the Antarctic Ice Sheet(s) expanded in the late Miocene and never withdrew significantly after that (Marchant and Denton, 1996; Warnke et al., 1996; Marchant et al., 2002). Another hypothesis suggests that polar conditions with fringing ice shelves of the East Antarctic Ice Sheet only developed in the mid Pleistocene (Raymo et al., 2006). We anticipate that the 2.9–2.0Ma diatom record from the AND-1B core will enable us to determine the timing of major climate and environmental transitions and how they relate to regional and global climate events.

2. Material and method

The AND-1B drillcore was recovered from the southeastern part of Victoria Land Basin (77.889° S; 167.089° E) beneath the Ross Ice Shelf in 930m of water where currently no in situ diatom production takes place. This basin has resulted from a combination of extensional rifting and structural loading associated with Ross Island volcanism (Naish et al., 2007). The upper 585m of the total 1285m of core comprise diatomaceous sedi-

[1] This interval of core was included as late Pliocene in the initial reports (Naish et al., 2007; Scherer et al., 2007; Wilson et al., 2007a, 2007b) and in Naish et al. (2009). However, with the IUGS ratification of the Pliocene/Pleistocene Boundary at 2.58Ma (Gibbard et al., 2010), we now refer to this interval as late Pliocene–early Pleistocene.

ment interbedded with diamicton, mud and volcanic sediment (Krissek et al., 2007). The 2.9–2.0Ma, 225–150m below sea floor (mbsf) comprises four diatom biostratigraphic units,

DU-VII to DU-IV, composed of several smaller sub-units (Scherer et al., 2007) (Fig. 2). Microscope diatom slides were prepared by disaggregation of samples in H2O2 and HCl, followed by rinsing in distilled water. Cemented samples were treated with 5% Calgon over night. A suspension of the cleaned sediment was dried onto a cover slip, mounted with Norland Adhesive 61 and cured under UV light. Diatom analyses, minimum 300 valves counted per slide, were performed on an Olympus BX51 microscope with a 100× oil immersion lens. Girdle bands of *Dactyliosolen antarcticus* occurring in abundance in limited parts of the record are only counted as one "valve" if they occur attached to each other. Chrysophyte cysts were counted as a group and the ratio of Chrysophyte cysts versus total diatom counts were calculated to assess relative abundance. The diatom floral list is provided in Appendix 1.

3. Results

The interglacial diatomaceous sediment contains well-preserved diatom valves with limited dissolution even though broken diatom valves are common. The abundance of representative species is presented as percent of the total assemblage together with the ratio of Chrysophyte cysts to total diatom count in Fig. 2. The complete data set is available on request. We use the diatom zone designation presented in the initial report, DU-VII through DU-IV for the 2.9– 2.0Ma units (Scherer et al., 2007) with separation of sub-units shown by lower case letters. For biostratigraphic information we refer to Winter et al. (2010b). The chronology is based on Naish et al. (2009). The percentage data in parenthesis is the average abundance of the species within each sub-unit.

In DU-VII (223.60–211.90mbsf; age ca. 2.9Ma within the *Fragilariopsis bohatyi* zone) the characteristic species include *Shionodiscus tetraoestrupii* (*Thalassiosira tetraoestrupii*) (22.3%), *Thalassiosira inura* (14.0%), F. bohatyi (9.8%), *Thalassiosira teres* (3.5%), and *Stellarima stellaris* (1.6%). Present in low abundances are *Stellarima microtrias* (4.3%), the *Rhizosolenia* "pointed group" (of Crosta et al., 2005) (2.3%), *Fragilariopsis curta* (2.2%), and *Eucampia antarctica* (1.2%) (Fig. 2). Chrysophyte cysts are present with a ratio of 0.013, and *Distephanus* speculum occurs randomly.

In DU-VI (202.90–183.43mbsf; ages 2.9–2.5Ma; within the *Actinocyclus fasciculatus–Actinocyclus maccollumii*-Concurrent Range Zone), the Gauss–Matuyama boundary (and now the Pliocene– Pleistocene boundary) at 2.58Ma is located at 191.75mbsf (Wilson et al., 2007a, 2007b). This unit is divided into four sub-units, a–d (Fig. 2). Sub-units a and b are separated by a diatom assemblage shift, sub-unit c comprises diatom bearing diamicton, and sub-unit d is separated from the underlying unit by a diamictite and volcanic section.

The dominant species in DU-VIa (202.90–197.70mbsf) is *S. tetraoestrupii* (24.5%), together with *Rouxia antarctica* (15.6%), *Actinocyclus karstenii* (12.5%), and *Fragilariopsis robusta* (6.5%). Characteristic for this unit is a peak

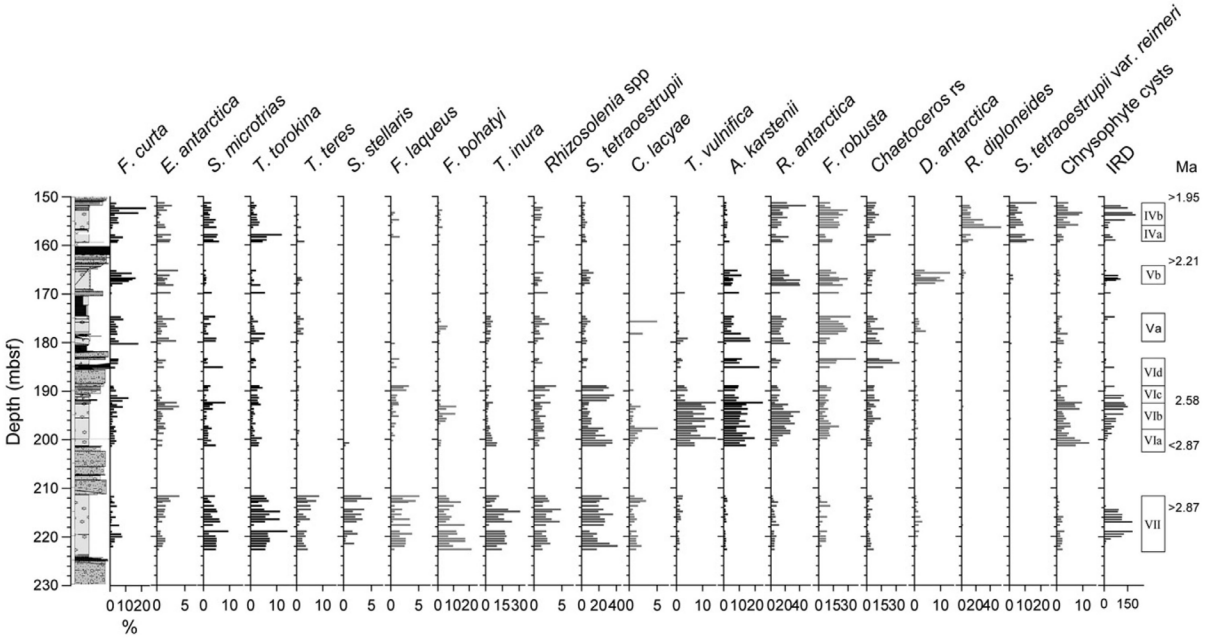

Figure 2. The lithologic log of the early late Pliocene AND-1B with the diatomaceous units marked in roman numerals. The diatom chart shows the most representative species in percent abundance. The far right column shows the ice rafted debris (IRD) from Talarico et al. (this volume).

abundance of *Thalassiosira vulnifica* (6.3%). Decreasing in abundance are *S. stellaris*, *T. inura* and *F. bohatyi*. *Fragilariopsis curta* (2.4%) remains in low abundance together with *S. microtrias* (2.2%) and *E. antarctica* (0.6%). Chrysophyte cysts increase to a maximum ratio of 0.055.

In DU-VIb (197.70–192.42mbsf) the abundance of *S. tetraoestrupii* decreases to 7.8% whereas *A. karstenii* and *T. vulnifica* remain stable and *R. antarctica* increases to 23.6%. *Fragilariopsis curta* increases slightly through this zone but remains in low abundance (2.7% with a peak of 7.7%). *Stellarima microtrias* (2.0%) and *E. antarctica* (1.6%) have similar trends to *F. curta*. The ratio of Chrysophyte cysts decreases to 0.046. In DU-VIc (192.42–189.00mbsf), the most striking differences from the previous unit are the high abundance of *S. tetraoestrupii* (29.8%), and a decline in *T. vulnifica* (2.3%) and the ratio of Chrysophyte cysts (0.022). In the last part, DU-VId (189.00–183.43mbsf) records a decrease of *S. tetraoestrupii* (4.6%) which remains in low abundance through the remaining part of the record, and an increase in *Chaetoceros* resting spores (rs) (21.6%) and *F. robusta* (20.7%).

DU-V is divided into sub-units a and b (180.66–174.70; 168.20– 164.20mbsf, ages 2.58–2.2Ma within the *Actinocyclus fasciculata– Actinocyclus maccollumii* zone). In DU-Va the dominant taxa are *R. antarctica* (15.9%) and *F. robusta* (19.5%). Other important species in the assemblage are *Chaetoceros rs* (8.4%), *A. karstenii* (7.2%) and *S. tetraoestrupii* (4.6%). *F. curta* is present with an average of 5.4%, and *E. antarctica* with 1.6%. In the upper half of this interval girdle bands of *Dactyliosolen antarcticus* appear in low but consistent abundance (1.1%). DU-Vb is separated from DU-VIa by a muddy facies with poor preservation of diatom valves, and characterized by laminated sediment and a distinctly different diatom assemblage. Dominating the assemblage are *R. antarctica* (25.8%), *F. robusta* (17.2%), *F. curta* (9.2%) and *D. antarcticus* (6.5%). The ratio of Chrysophyte cysts in this unit (0.005) is the lowest in the 2.9–2.0Ma record.

The last diatomaceous unit of the 2.9–2.0Ma record is DU-IV which is also divided into two sub-units a and b (a—159.23–157.84; b—156.30– 150.80mbsf; ages 2.2–2.0Ma within the *Rouxia antarctica*–Partial Range Zone and sub-zone a). Most significant in DU-IVa is the appearance of *R. diploneides* (10.1%) and *S. tetraoestrupii* var. *remerii* (4.2%). Increasing in abundance are *Thalassiosira torokina* (7.0%) and *S. microtrias* (4.8%). Remaining in high abundance are *R. antarctica* (14.9%) and *F. robusta* (9.8%) whereas *F. curta* decreases in abundance (5.0%). The ratio of Chrysophyte cysts increases slightly to 0.018.

In DU-IVb *R. antarctica* and *F. robusta* remain in high abundance with *R. antarctica* increasing towards the top. The abundance of *Rouxia diploneides* decreases through this sub-unit. *A. karstenii* drops to an abundance of 1.3%. *F. curta* appears in two prominent spikes of 22% and 17%, however the average is 6.4% (excluding the two peaks 3.4%). The ratio of Chrysophyte cysts increase to 0.047.

4. Discussion

To evaluate past environmental change, knowledge of ecological preferences for the different species is required. This presents a problem when dealing with assemblages that are dominated by extinct and newly described species which preclude the use of transfer functions based on modern assemblages. We approach this problem by comparing AND-1B assemblages both to modern data sets and to species abundance data across oceanic zones over the last 3Ma utilizing material from a set of DSDP/ODP cores (Figs. 1, 3). For a list of sites see Section 4.1.1. We distinguish three zones: sub-Antarctic (SAZ), Permanent Open Ocean (POOZ) and Seasonal Sea Ice (SIZ).

4.1. Modern assemblages

We employ the diatom environment classification defined in the modern Southern Ocean from the DD228 data base of diatom abundance in surface sediment (Armand et al., 2005; Crosta et al., 2005; Romero et al., 2005); sea-ice species, open-ocean species and tropical/subtropical species, with some modification.

The AND-1B sea-ice assemblage comprises *Actinocyclus actinochilus*, *E. antarctica*, *F. curta*, *Fragilariopsis cylindrus*, *Fragilariopsis obliquecostata*, *Fragilariopsis ritscheri*, *Porosira* spp., *S. microtrias* and *Thalassiosira tumida*. *Chaetoceros rs* are commonly viewed as indication of surface water stratification in association with a receding ice edge (Leventer et al., 1996; Sjunneskog and Taylor, 2002; Crosta et al., 2004). Because the *Chaetoceros rs* group occurs in high abundance north of the polar front in the Pliocene (Fig. 3) and is also associated with upwelling water masses we have excluded them from the sea-ice assemblage (included in the DD228 data set). Furthermore, this group is shown to have a bi-parted distribution pattern in the Bellinghausen Sea with one cluster at the summer sea ice edge and one at the Sub Antarctic Front (Esper et al., 2010).*WehaveelectedtoincludeE. antarctica* in the sea-ice assemblage (excluded from DD228) since it is considered a tracer for sea-ice concentration, for example see the Eucampia index of Whitehead et al. (2005), and it has a less diverse distribution through time as compared to *Chaetoceros rs* (Fig. 3).

The open-ocean assemblage includes the *Rhizosolenia* pointed group (without *Rhizosolenia harwoodii*, R. sp D of Harwood et al., 1982; extinct in the late Pleistocene), the *Thalassiothrix–Trichotoxon* group, *Thalassiosira lentiginosa* and *Thalassiosira oliverana*. Two species that are part of this group in Crosta et al. (2005), *Fragilariopsis kerguelensis* and *Thalassiosira gracilis*, occur as a few specimens total in the AND-1B record and hence do not contribute substantially to the assemblage. Also included in the

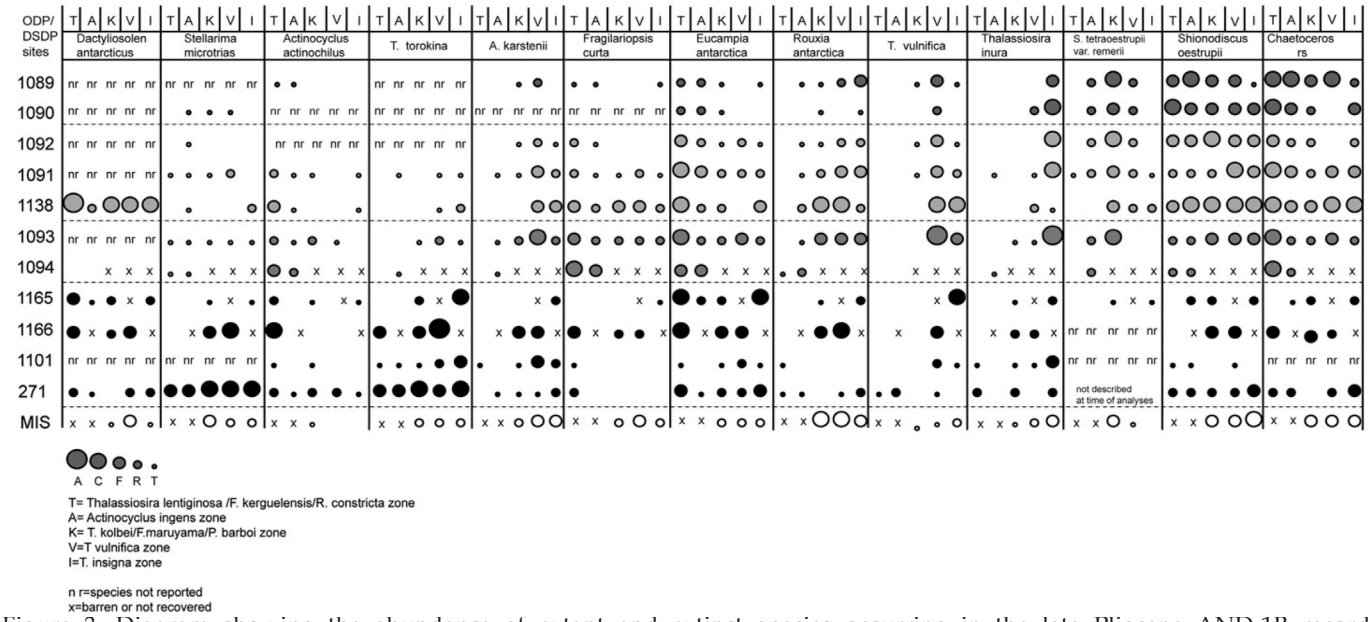

Figure 3. Diagram showing the abundance of extant and extinct species occurring in the late Pliocene AND-1B record. This figure presents the average abundance of these species as reported in respective DSDP/ODP volume. The diatom abundance data is extracted from the ODP Scientific Results Volumes 177 (Zielinski and Gersonde, 2003), 178 (Winter and Iwai, 2002) and 188 (Whitehead and Bohaty, 2003), from Zielinski and Gersonde (2002) and for DSDP Leg 28 Site 271 (Winter, unpublished data). The diatom zonations have been grouped to provide a general model (and avoid the complication of a different zonation system) with an easy overview. The top of the graph represents the sub-Antarctic zone whereas the lower part shows continental shelf sites. A=abundant, C=common, F=frequent, R=rare, T=trace.

POOZ assemblage is *D. antarcticus*, the environmental constraints are not well established for this species but it is commonly attributed an open-ocean habitat (Taylor et al., 1997;Whitehead and McMinn, 2002).

The subtropical/subantarctic group is represented by *S. stellaris* and *S. tetraoestrupii*. The latter may be included in the *S. oestrupii*-group in the DD228 data set (Romero et al., 2005). Both of these species are however considered sub-Antarctic species (Marlow et al., 2000;Whitehead et al., 2001) and have a distinct distribution in the AND-1B core. SEM studies of AND-1B samples have shown that the modern *S. oestrupii* is not present in our record but is morphologically indistinguishable from *S. tetraoestrupii* in the light microscope. We infer the same environment for these two species; they have not always been separated in previous ODP records and other authors suggest that different varieties of the *S. oestrupii*-group are associated with the sub-Antarctic zone (Crosta et al., 2004), hence we have considered them con-specific until their temporal distribution can be resolved.

4.1.1. Late Pliocene–early Pleistocene records

To address the paleoenvironment of extinct species we plotted mid-Pliocene to Pleistocene diatom distributions from DSDP and ODP sites located across the sub-Antarctic and Polar Frontal Zones and the continental shelf (Fig. 3).Many different diatombiostratigraphic zones and sub-zones have been employed through continuous updates (Harwood and Maruyama, 1992). To achieve an overview we have grouped these into broad categories and it has to be emphasized that this is a generalization intended to show trends. The diatom abundance data is extracted from the ODP Scientific Results Volumes 177 (Zielinski and Gersonde, 2003), 178(Winter and Iwai, 2002) and 188(Whitehead and Bohaty, 2003), from Zielinski and Gersonde (2002) and for DSDP Leg 28 Site 271 (Winter, unpublished data). The last site is included despite the use of old taxonomy because of its relative proximity to the AND-1B site. These records show that *R. antarctica* and *T. vulnifica* occur in a wide range of latitudes whereas *A. karstenii* and *T. torokina* appear to have an affiliation to higher latitudes. Most abundant in the sub-Antarctic zone are *T. inura*, *S. tetraoestrupii* var. *remerii* and *S. oestrupii–tetraoestrupii*. The records of *D. antarcticus* and *S. stellaris* are sporadic (*S. stellaris* not shown in Fig. 3). Their occurrence is difficult to compare to previous work because we believe that neither is consistently reported. This may be because only the girdle bands of *D. antarcticus* are preserved in the sediment and *S. stellaris* is commonly grouped with *S. microtrias*.

4.2. AND-1B 2.9–2.0Ma diatom record compared to the modern diatom environmental groups

4.2.1. Sea ice

The total abundance of sea ice indicator species is fairly low in the late Pliocene record ranging from 2.0% to 29.6%, with an average of 9.7%. The most extensively used sea-ice indicator is *F. curta*. This species is currently restricted by the northernmost extent of sea-ice and occurs only in trace abundance north of this limit; excursions are believed to be associated with drifting ice bergs (Zielinski and Gersonde, 1997; Armand et al., 2005). In the modern near shore Western Ross Sea F. curta reaches abundances from ca. 20% to 85% (Cunningham and Leventer, 1998; Armand et al., 2005). The highest abundances are linked to highly consolidated sea ice present for 9–11months per year and abundances less than 40% appear to be unrelated to summer sea-ice extent (Armand et al., 2005). In the AND-1B record, abundances near 20% are only reached in three isolated peaks of the 2.9–2.0Ma interval (Fig. 2). The only longer consistent (multisample) period of increased *F. curta* is in association with an unusual abundance of *D. antarcticus* in a laminated section of DU-Vb. An abundance of 3% has been employed to assess Pleistocene and Holocene winter sea-ice limit (Zielinski and Gersonde, 1997; Kunz-Pirrung et al., 2002; Crosta et al., 2004); the 2–6% abundance range of *F. curta* from the 2.9–2.0Ma AND-1B record implies that the AND-1B site was close to the winter sea ice edge and that the sea ice presence was of short duration. The northern Antarctic Peninsula region experiences extensive seasonal sea ice for 6–7month of the year and the abundance of *F. curta* is commonly only a few percent in the sediment (Leventer et al., 1996; Sjunneskog and Taylor, 2002; Heroy et al., 2007). Here *Chaetoceros* spp. forms blooms at the receding melting ice edge where surface water stratification develops and the resting spores make up 70–80% of the sediment diatom assemblage. In the AND-1B record, *Chaetoceros rs* only occur in ca 5–10% except for unit DU-VIb (see below). The low abundance of *Chaetoceros rs* further supports that sea ice was of limited extent and/or duration. Sea ice formation is dependent on wind stress in addition to air and water temperature (Jacobs et al., 2002), and it is possible that increased wind regime prevented buildup of sea ice during the late Pliocene– early Pleistocene. However the absence of a modern cold open water assemblage suggests warmer SST and possibly higher salinity.

The Eucampia sea-ice index (Whitehead et al., 2005) could not be applied in the AND-1B core because terminal valves of E. Antarctica are rarely encountered in the late Pliocene–early Pleistocene. The valves encountered are broken so that species varieties cannot be assessed. In the modern environment, terminal valves increase in abundance when *E. antarctica* grows in sub ice-shelf/sea-ice conditions, hence the near absence of these valves suggest that sea-ice concentration was low.

The only individual sea-ice species that reaches the same relative abundance as in the modern sediment is *S. microtrias* which prefers ice-free conditions during the summer when it is present at its maximum abundance (3.2% in DD228) but it also indicates a winter sea-ice concentration of >65% and ca. 7.5month of ice cover, and the temperature optimum is −1.3 to +3.5°C (Armand et al., 2005). The individual species within the extant sea-ice assemblage have their FAD prior to or during the studied interval, with the exception of one species (*T. antarctica*), however the modern sea-ice assemblage is not established by 2.0Ma which may indicate that the modern sea ice, fast ice and ice shelf environment was not yet in existence by 2.0Ma.

4.2.2. Open ocean

The average abundance of the open-ocean group, 4.6%, is evenly distributed throughout the investigated interval with the exception of the laminated sediment interval of DU-Vb where a maximum abundance of 15.8% is reached. The dominant open ocean species of the Pleistocene, *F. kerguelensis* and *T. lentiginosa*, are rare in the 2.9–2.0Ma record of AND-1B. The *Rhizosolenia* pointed group of Crosta et al. (2005) is represented in abundances of up to 3% which is in the vicinity of the abundances present in modern surface sediment where it has an optimal temperature range of 1–1.5°C (Crosta et al., 2005), whereas the *Thalasiotrix/Thalassionema* group is only present in trace abundance. Most likely this poor representation of the open-ocean group is an expression of environmental control on distribution; the continental shelf does not, and did not provide the habitat of the Polar Front Zone where this group thrives. Similar to this investigation, the open ocean group, except *F. kerguelensis*, did not show a significant change between glacial and interglacial periods in the late Pleistocene (Crosta et al., 2004) and was less important in the paleoclimate reconstruction.

4.2.3. Sub-Antarctic

The 2.9–2.0Ma AND-1B record does not contain the complete assemblage observed north of the modern subAntarctic Front. Of the two species representing warmer conditions, *S. stellaris* only occurs in low abundance in a limited section of the late Pliocene, DU-VII and the lowermost part of DU-VIa (Fig. 2). *S. tetraoestrupii* shows a very distinct distribution in the core and is abundant (>20%) in units DU-VII and DU-VI but diminishes to ca. 4% in the younger units. In the modern near shore Antarctic environment *S. oestrupii* is only present in trace abundance (Romero et al., 2005). The high abundance of *S. tetraoestrupii* in the late Pliocene record implies warmer than present conditions during at least part of the growth season. *Shionodiscus oestrupii* occurs with a maximum abundance of 21% at 12–19°C with a lower temperature range of 4.5°C (Romero et al., 2005). However, it should be noted that inferring the same

environment for these two presumed related species, *S. oestrupii* and *S. tetraoestrupii*, is circumstantial and it is necessary to establish the distribution of these two species in previously obtained records to resolve any environmental differentiation.

4.3. Paleoenvironment interpretation

Comparison of the AND-1B record to the modern outer shelf and open ocean diatom assemblages clearly demonstrates that the late Pliocene continental shelf environment lacks a modern analog. It is evident that even though many of the diatom species had their first appearance prior to, or in the late Pliocene these species were not established on the continental shelf during the late Pliocene suggesting an environmental segregation and a unique environment.

Temperate summer conditions during deposition of DU-VII (2.9Ma) are suggested by the presence of *S. stellaris* and the high abundance of *S. tetraoestrupii* (22%). Supporting an interpretation of warmer conditions is the high abundance of *T. inura* that is associated with the more northerly water masses (Fig. 3), and the presence of the new species *T. teres* (Winter et al., 2010a) common in sections of the mid Pliocene together with *S. stellaris* and *S. tetraoestrupii*. The presence of winter sea ice is indicated by the scattered occurrence of *F. curta*, and the low consistent presence of *S. microtrias* and *E. antarctica*. Of the abundant extinct species *T. torokina* appears to be associated with colder or more neritic conditions (Fig. 3). The co-occurrence and high abundance of *F. laqueata*, *F. bohatyi*, and *S. tetraoestrupii* suggest these are associated with warmer conditions compared to the late Pleistocene–Holocene Fragilariopsis flora which is associated with the modern seasonal sea ice zone (Sjunneskog et al., in press).

The low concentration of *Chaetoceros rs* suggests that the ice sheet and outlet glaciers terminate on land with little freshening and stabilization of surface water, which is in agreement with the low concentration of IRD in the early part of the record (DU-VII) and with the suggestion that less than 30% of *Chaetoceros rs* are not associated with sea ice (Armand et al., 2005). The higher IRD abundance in the later part of the record is not associated with a change in diatom assemblage and it is unclear how these proxies relate. In agreement with our interpretation of a relatively warm period during DU-VII is a paleotemperature record from the Kerguelen Plateau based on a ratio of silicoflagellate species that suggests a SST ca. 3–4°C warmer during the 3.1–2.64Ma period (Whitehead and McMinn, 2002).

Perhaps the most significant change in diatom assemblage composition takes place between DU-VII and DU-Via, separated by ca. 250kyr hiatus (Naish et al., 2009). In DU-VIa *S. tetraoestrupii* remains in high abundance suggesting continued warmer than present conditions. A cooling trend may be indicated by the disappearance of *S. stellaris*, the decrease of *T. inura* that made up a significant part of the assemblage in the previous unit (Fig. 2); and a substantial increase in abundance of several extinct species. Of these *A. karstenii* is associated with the cold open water zones, but both *T. vulnifica* and *R. antarctica* appear in all oceanic zones (Fig. 3) indicating that distribution of these species is governed by factors other than SST. Of importance here is the high ratio of Chrysophyte cysts indicative of freshwater input, and often associated with melting sea ice and melt water on the ice shelf; an environment that is not supported by the continued low abundance of sea ice species. The combination of *S. tetraoestrupii* and Chrysophyte cysts could indicate that local outlet glaciers had developed marine termini, releasing melt water in contact with the relatively warm marine waters.

In the stratigraphic sub-unit, DU-VIb, *S. tetraoestrupii* and Chrysophyte cysts decrease in abundance whereas *R. antarctica* increases as does the amount of IRD (Fig. 2). This implies a relative cooling of the surface water within this interglacial and that *T. vulnifica* and *R. antarctica* tolerate fresher water better than *S. tetraoestrupii* which, as a sub-Antarctic species, prefers higher salinity. Whitehead and McMinn (2002) suggested that *R. antarctica* is associated with summer pack ice north of the seasonal sea ice zone in early Quaternary glacial periods, but also concluded that this species has a positive correlation to warmer conditions during the Pliocene– Pleistocene and hence that temperature is not the only control on the distribution. This is in agreement with our species versus age plot (Fig. 3) showing that *R. antarctica* occurs over a wide range of latitudes. An alternative explanation for the high abundance of Chrysophyte cysts in the sediment is a release of melt-water from land, such as ice dammed lakes, but there is no sedimentological evidence of rapid release of freshwater and no evidence of a freshwater diatom assemblage.

Diatom unit DU-VIc is characterized by varying amounts of incorporated diamicton and faulting, and it is unclear if this section represents a single relatively warm interglacial or a fluctuating grounding line and locally reworked sediment (Fig. 2). Within this sub unit, *S. tetraoestrupii* reaches its highest abundance. However the flora displays an unusual range of different morphologies and sizes skewed towards smaller specimens, which may signal environmental stress. The assemblage does not appear to be reworked from the underlying DU-VIb that towards the top contains higher abundance of *E. antarctica* and *S. microtrias* both commonly enriched in reworked assemblages (Sjunneskog and Scherer, 2005).

The diatom assemblage of the youngest sub-unit, DU-VId, is markedly different from below and hence indicates another step in environmental change. The dominant species are *F. robusta*, *Chaetoceros rs* and *R. antarctica*. *Chaetoceros rs* are associated with high primary

productivity in the vicinity of the melting sea ice edge where it commonly makes up 80% or more of the sediment diatom assemblage and often form laminae (Leventer et al., 1996; Sjunneskog and Taylor, 2002; Crosta et al., 2004; Maddison et al., 2005; Stickley et al., 2005). However, in the species distribution plot, *Chaetoceros rs* are recorded more frequently and abundantly in the sub-tropical zone compared to the Antarctic Zone (Fig. 3). *F. robusta* is suggested to be an ancestor to *F. obliquecostata* (Sjunneskog et al., in press), a species that today is associated with winter sea ice habitats where it occurs at a maximum abundance of ca. 10% at the SST optimum between ca. − 1 to 0°C (Zielinski and Gersonde, 1997; Cunningham and Leventer, 1998; Cunningham et al., 1999; Armand et al., 2005). The inferred link between *F. robusta* and *F. obliquecostata* and its increase as the warm water taxa *T. inura* and *S. tetraoestrupii* decrease suggests that *F. robusta* also inhabits a cold open water environment. Based on the available data we propose a cold water environment with surface water stratification for this sub-unit.

Separating the DU-Va assemblage from the underlying assemblages is the presence of *D. antarcticus* (Fig. 2). This species has been used to infer warmer conditions in East Antarctic Pliocene sediment (Whitehead et al., 2001), and it was placed in a Pliocene open ocean zone together with *T. oestrupii* in a paleoenvironmental record from the Kerguelen Plateau (Whitehead and McMinn, 2002). It is noted as common in the open ocean beyond the present winter sea ice limit at ODP Site 1138 (Fig. 3) and appears to be associated with the polar front and open ocean assemblages (Taylor et al., 1997). In DU-Va, it occurs together with *F. robusta* and *R. antarctica*, which together suggest cold open water conditions.

In DU-Vb, separated from DU-Va by mud sequences, *D. antarcticus* and *F. curta* both peak in abundance in a sub-mmscale laminated sediment indicating surfacewater stratification, or repeated high productivity events and mass deposition (Leventer et al., 1996). Themorphology of Dactyliosolen may cause it to form aggregates or mats by wave action with subsequent mass deposition similar to Corethron and Thalassiothrix, for example ODP Leg 177 sites display frequent diatom mats composed of Thalassiothrix deposited in the late Pliocene and early Pleistocene (Zielinski and Gersonde, 2002). Thalassiothrix does not comprise a dominant role in the AND-1B samples albeit common in discrete laminae (Maffioli et al., 2009). For this site, the high abundance of *F. curta* (ca.10%) favors the interpretation of surface water stratification and local sea ice melt although *Chaetoceros rs* are not present in high abundance. However, we do not see any evidence in the diatom record of substantially colder conditions or sea-ice or ice-shelves similar in extent to the present interglacial.

The final step of major diatom assemblage change takes place in the transition to DU-IV where *A. karstenii* is reduced to a few percent and *R. diploneides* and S. tetraoestrupii var. reimeri become abundant (Fig. 2). The diatom assemblage composed of *Rouxia* species, *F. robusta* and *T. torokina* in combination with the high abundance of Chrysophyte cysts and increased IRD suggests cold open-water conditions similar to the winter sea-ice edge today and quite possibly ice shelves in the coastal zone. In the uppermost part of the interval studied *A. actinochilus* appears expressing a much abbreviated presence in the core compared to its total age range (Scherer et al., 2007), also *F. obliquecostata* appears as just few specimens. *A. actinochilus* is a member of the modern sea-ice assemblage where it is associated with significant winter sea-ice cover and openwater during the summer (Armand et al., 2005), similar to *S. microtrias* which also increases in abundance within this unit. Even with the increase of sea ice species, *F. curta* remains in relatively low abundance, with the exception of a few spikes, indicating that ice conditions of Holocene proportions are not yet established by ca. 2.0Ma. The preferred environment for *R. diploneides* is not well known, but *S. tetraoestrupii* var. *reimeri* appears to have an affiliation to more northerly water masses based on the ODP core plot (Fig. 3) and hence contradicts a cooling trend. It is possible the summer SST was high enough to support a species of the *S. oestrupii–tetraoestrupii* group during brief periods. It is also possible that the distribution of *S. tetraoestrupii* var. *reimeri* is governed by other environmental factors such as nutrient availability or salinity.

The diatom assemblages illustrate a cooling trend through the late Pliocene–early Pleistocene where the abundance of species associated with warmer-than-present SST shows two steps of change; at 2.9 and 2.5Ma, whereas the extinct assemblages indicate successive cooling. Strikingly, the abundance of sea-ice species only increases slightly indicating the limited extent and presence of summer sea ice in the McMurdo region also during the early Pleistocene. Sea ice is present throughout the record but is more extensive after the transition from DU-VII to DU-VI when *R. antarctica*, *A. karstenii* and *F. robusta* drastically increase in abundance, but not in significant amounts until DU-IV that records a last shift in diatom assemblage. This also implies none or poorly developed fast ice and shelf ice during these previous interglacials.

4.4. Circum Antarctic diatom records

Sediment of late Pliocene–early Pleistocene age are recovered from a few sites around the Antarctic continent, these include the Kerguelen Plateau (Whitehead and McMinn, 2002), Prydz Bay (Mahood and Barron, 1996; Whitehead et al., 2005), and Bardin Bluffs (Whitehead et al., 2004).

In a series of gravity cores across the Kerguelen Pla-

teau, late Pliocene sediment sequences separated by hiatuses were sampled (Whitehead and McMinn, 2002). A Pliocene, 3.1–2.64Ma, Antarctic open-ocean assemblage was identified with high abundances of *T. oestrupii* (now *S. oestrupii*) and *D. antarcticus*. This assemblage was associated with higher than present SST, ca. 4°C, based on the species of silicoflagellates present (Whitehead and McMinn, 2002). DU-VII chronostratigraphically corresponds to this time period and the assemblages share similarities, the high abundance of *S. tetraoestrupii* at both sites strengthens the inferred warmer oceanic conditions in McMurdo Sound. A late Pliocene–early Pleistocene assemblage composed of *F. curta*, *Thalassiosira* species, and *Rouxia* species was suggested to represent summer glacial conditions with light pack ice on the Kerguelen plateau. The Kerguelen pack-ice (*Rouxia*) assemblage shares few similarities with the DU-IV and V assemblages, the differences include the *Thalassiosira* species composition and the much higher abundance of *F. curta* in the Kerguelen record, 21% versus 9% in the AND-1B record. We propose that during stage DU-IV fall–spring conditions were similar to the glacial summer conditions on the Kerguelen Plateau. The hiatuses in the Kerguelen record were proposed to be caused by intense glaciations and increased velocity of the Antarctic Circumpolar Current; the youngest hiatus at 2.2–1.6Ma corresponds to the time of a major unconformity (Rk) in AND-1B (2.0–1.6Ma) and suggests a major cooling and sea-ice and shelf ice formation took place post 2.0Ma (Naish et al., 2007). This time interval corresponds to the period of subtropical/tropical climate reorganization proposed to be associated with a second step of Pliocene climate cooling after the initiation of the Northern Hemisphere ice sheet (Ravelo et al., 2004).

Evidence for late Pliocene–early Pleistocene retreat of the marginal EAIS has been obtained from Prydz Bay by ODP Legs 113 and 188 (Mahood and Barron, 1996; Whitehead et al., 2005). At ODP Site 742 a diatomaceous unit was recovered sandwiched between diamict units. This unit was biostratigraphically dated to ca 2.2–1.8Ma (Mahood and Barron, 1996) and has a diatom assemblage very similar to DU-IV, this assemblage is also encountered in piston core sediments from the Northern Basin of Ross Sea (Sjunneskog et al., 2009) and Site 274 (DSDP Leg 28) (Fleming and Barron, 1996).

Other interglacial records that overlap with the AND-1B 2.9–2.0Ma interval include those found at Bardins Bluff in the Pagodroma Group (Prydz Bay) that comprises tectonically uplifted open-marine diatom deposits with a reduced sea-ice flora dated to 2.6–1.8Ma (Whitehead et al., 2004). Another is a sequence from the Northern Antarctic Peninsula, the Cockburn Island Formation, that comprise a late Pliocene uplifted sediment carrying evidence of open-marine deposition ca. 3–2.8Ma (Jonkers and Kelley, 1998). Together, the siliceous microfossil records from these sites imply a very dynamic margin of the EAIS and warmer than present conditions until ca 2.0Ma.

Modeling, using a combined ice sheet–ice shelf model, indicates that the WAIS may have experienced brief collapses during the late Pliocene but fewer and shorter compared to the Pliocene climatic optimum, 3.6–3.4Ma, (Pollard and DeConto, 2009). In this model, sub ice-shelf melting proved to be the most important factor in rapid ice shelf retreat, which is in agreement with the findings of a poorly developed summer sea ice flora at AND-1B as well as in Prydz Bay (Whitehead et al., 2005). Sea-ice/ice-sheet modeling has indicated the requirement of a fully glaciated East Antarctic Ice Sheet to enable sea-ice and ice-shelf expansion of modern proportions (DeConto et al., 2007). This model also indicates that sea ice is sensitive to orbital forcing once the ice sheets are established. The presence of sea-ice has a fundamental effect on the near coast climate through increased albedo and limiting CO2 exchange. Furthermore, sea-ice formation produces Antarctic Bottom Waters that plays an important role in global ocean circulation but has only minor effects on the continental interior. Understanding the sea-ice record of the Pliocene–Pleistocene is clearly a vital part of understanding the climate system; the diatom record from AND 1-B of reduced sea-ice and relatively warm SSTs extending into the late Pliocene–early Pleistocene shows that even extreme high latitude coastal environments responded to external forcing and are important for assessing the stability of ice shelves and marine ice sheets such as the West Antarctic Ice Sheet.

The conditions in McMurdo Sound during a large part of the late Pliocene–early Pleistocene suggests that the coastal areas must have had minor fringing ice shelves and most likely glaciers terminated on land in interglacial periods. It seems likely that some local drawdown of the EAIS would have occurred during these periods.

The Pliocene cooling in the AND-1B record began at ca 3.3Ma (McKay et al., 2012), and the cooling continued through the late Pliocene. The first cooling step in the late Pliocene of the AND-1B diatom record occurs at ca 2.9Ma and the second change in diatom inferred climate change took place sometime after 2.58Ma and prior to 2.2Ma which corresponds to the time of a maximum Northern Hemisphere ice sheet which occurred between 2.7 and 2.55Ma (Maslin et al. 1998). The final cooling step within the studied interval is recorded here as occurring at ca 2Ma.

5. Conclusion

This overview of the 2.9–2.0Ma diatom record of AND-1B reveals very dynamic period with an overall pattern of stepwise cooling DU-VII (2.9Ma) was a relatively warm period indicated by the presence of *S.*

tetraoestrupii and *S. stellaris* and correlation to assemblages present at off-shore sites, the SST may have reached ca. 3°C and this appears to represent the tail end of the mid-Pliocene warm period. The loss of warm water indicators is documented in two stages, between DU-VII and DU-VI ca 2.9Ma and after 2.58Ma (Fig. 2). The microfossil record suggests that glaciers developed marine termini during DU-VI 2.6Ma when freshening of the water column is indicated by increase of Chrysophyte cysts. However, no freshwater diatom flora is detected. The last step of the cooling trend occurs with DU-IV when *R. diploneides* and *S. tetraoestrupii* var. *reimeri* are introduced to the assemblage, and *A. actinochilus* and *F. obliquecostata* which are part of the modern sea ice and cold water assemblage appear. The modern sea-ice assemblage and the present day cold conditions are not yet established by 2.0Ma which indicates that the interglacial summers of the late Pliocene–early Pleistocene remained largely ice free. The many hiatuses in the record and therefore limited chronology prevents an absolute correlation to the Northern Hemisphere cooling events.

The diatom record from the AND-1B provides ample information regarding sea ice and SST during the late Pliocene through early Pleistocene. The extant assemblages are not well represented in the late Pliocene AND-1B record which implies significantly different coastal marine conditions. The comparison with both modern and extinct assemblages allows us to bracket the environmental information within a range of sea ice and SST. However, to utilize fully the paleoenvironmental potential of this Pliocene diatom record, and for global correlation, more taxonomic work needs to be undertaken, in combination with re-investigation of old core material. This will help obtain a refined paleoenvironmental record for this and future sites to be investigated.

Acknowledgments – This material is based upon work supported by the National ScienceFoundation under Cooperative Agreement No. 0342484 through subawards administered by the ANDRILL Science Management Office at the University of Nebraska-Lincoln, and issued through Northern Illinois University (for the MIS Project), as part of the ANDRILL U.S. Science Support Program. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

The ANDRILL (ANtarctic geologic DRILLing) Program is a multinational collaboration between the Antarctic Programs of Germany, Italy, New Zealand and the United States. Antarctica New Zealand is the project operator and has developed the drilling system in collaboration with Alex Pyne at Victoria University of Wellington and Webster Drilling and Exploration. The U.S. Antarctic Program (USAP) and Raytheon Polar Services Corporation (RPSC) supported the science team at McMurdo Station and in the Crary Science and Engineering Laboratory, while Antarctica New Zealand supported the drilling team at Scott Base. Scientific studies are jointly supported by the US National Science Foundation, NZ Foundation for Research, the Italian Antarctic Research Program, the German Science Foundation and the Alfred Wegener Institute.

Samples were provided by the Antarctic Marine Geology Research Facility (AMGRF). We also thank Matt Olney for insightful comments on the manuscript.

Appendix 1

Late Pliocene species list.

Achnanthes spp.
Actinocyclus actinochilus (Ehrenberg) Simonsen
Actinocyclus fasciculatus Harwood et Maruyama
Actinocyclus ingens Rattray
Actinocyclus karstenii Van Heurck
Actinocyclus maccollumii Harwood et Maruyama
Actinocyclus octonarius Ehrenberg
Actinocyclus spp.
Actinoptychus spp.
Aulacodiscus browneii McCollum
Chaetoceros bulbosum (Ehrenberg) Heiden, in Heiden and Kolbe
Chaetoceros spp.
Cocconeis costata Gregory
Corethron criophilum Castracane
Coscinodiscus spp.
Creania lacyae Olney
Dactyliosolen antarcticus Castracane
Denticulopsis delicata Yangasawa et Akiba
Denticulopsis dimorpha (Schrader) Simonsen
Denticulopsis lauta (Bailey) Simonsen
Denticulopsis maccollumii Simonsen
Denticulopsis simonsenii Yanagisawa et Akiba
Denticulopsis spp.
Eucampia antarctica var *recta* (Mangin) Fryxell et Prasad
Fragilariopsis aff. *sublinearis* MIS
Fragilariopsis arcula (Gersonde) Gersonde et Bárcena
Fragilariopsis aurica (Gersonde) Gersonde et Bárcena
Fragilariopsis bohatyi Sjunneskog et Riesselman (Fig. 5, Nos. 1–3,Winter et al., 2010a)
Fragilariopsis curta (Van Heurck) Hustedt
Fragilariopsis interfrigidaria (McCollum) Gersonde et Bárcena
Fragilariopsis laqueata Riesselman
Fragilariopsis obliquecostata (Van Heurck) Hasle
Fragilariopsis praecurta (Gersonde) Gersonde et Bárcena
Fragilariopsis ritscheri Hustedt
Fragilariopsis robusta Sjunneskog
Fragilariopsis spp.
Fragilariopsis sublinearis (Van Heurck) Heiden
Fragilariopsis vanheurckii (Peragallo) Hustedt
Odontella weissflogii (Janisch) Grunow
Paralia sulcata (Ehrenberg) Cleve
Porosira pseudodenticulata (Hustedt) Jousé, in Kozlova
Proboscia barboi (Brun) Jordan et Priddle
Rhizosolenia spp.
Rouxia antarctica Heiden, in Heiden and Kolbe
Rouxia constricta Zielinski et Gersonde
Rouxia diploneides Schrader
Rouxia leventerae Bohaty, Scherer et Harwood 1998
Rouxia naviculoides Schrader

Rouxia spp.
Shionodiscus gracilis var. gracilis (Karsten) Alverson, Kang et Theriot
Shionodiscus tetraoestrupii (Bodén) Alverson, Kang et Theriot
Shionodiscus tetraoestrupii var. *reimeri* (Mahood et Barron) *Alverson*, Kang et Theriot
Stellarima microtrias (Ehrenberg) Hasle et P.A. Sims
Stellarima stellaris (Roper) Hasle et Sims
Stephanopyxis spp.
Stephanopyxis turris (Greville et Arnott) Ralfs, in Pritchard
Synedropsis cheethamii Olney
Synedropsis laevis (Heiden) Hasle, Medlin et Syvertsen
Synedropsis recta Hasle, Medlin et Syvertsen
Synedropsis spp.
Thalassionema/Thalassiothrix spp.
Thalassionema nitzschioides (Grunow) Van Heurck
Thalassiosira antarctica Comber
Thalassiosira complicata Gersonde
Thalassiosira elliptipora (Donahue, 1970) Fenner
Thalassiosira fasciculata Harwood et Maruyama
Thalassiosira insigna/inura
Thalassiosira inura Gersonde
Thalassiosira kolbei (Jousé, 1962) Gersonde
Thalassiosira lentiginosa (Janisch) Fryxell
Thalassiosira oliverana (O Meara) Sournia
Thalassiosira oliverana v. *sparsa* Harwood et Maruyama
Thalassiosira spp.
Thalassiosira striata Harwood et Maruyama
Thalassiosira teres Winter
Thalassiosira torokina Brady
Thalassiosira tumida (Janisch) Hasle in Hasle et al.
Thalassiosira vulnifica (Gombos) Fenner
Thalassiosira webbi Harwood et Maruyama
Thalassiothrix antarctica Schimper ex Karsten
Thalassiothrix spp.
Trinacria spp.
Chrysophyte spp.
Silicoflagelate spp.

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